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Extraction of ethanol with higher carboxylic acid solvents and their toxicity to yeast

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ABSTRACT

In a screening exercise for ethanol-selective extraction solvents, partitioning of ethanol and water from a 5 wt% aqueous solution into several C8–C18 carboxylic acids was studied. Results for the acids are compared with those from alcohols of similar structure. In all cases studied, the acids exhibited higher separation factor, but lower capacity than their alcohol analogs. Solvent toxicity to a commercial yeast commonly used in fuel ethanol production was evaluated for selected solvents. For the acids studied, those containing 12 or fewer carbons were toxic or inhibitory to the yeast; those containing 16 or more carbons were non-toxic and non-inhibitory.

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1. Introduction

The use of renewable feedstocks for conversion to transportation fuels is increasing rapidly. The first phase of production of fuel ethanol primarily used corn as feedstock. The second phase is beginning and will use lignocellulosic feedstocks. These feedstocks include residues and wastes such as corn stover, straws, forest residues, municipal solid waste, and fruit and vegetable processing wastes, as well as dedicated energy crops such as perennial grasses and fast-growing trees [1]. A difficulty with lignocellulosic feedstocks is that the fermentable C6 sugars that result from hydrolysis of cellulose are typically less concentrated than those that are derived from hydrolysis of the starch in grains. Significant amounts of soluble hemicellulose drive up the viscosity in the fermentor. In addition, fermentation inhibitors may be present, though this depends on the pretreatment hydrolysis method [2–4]. For these reasons, lignocellulose-based fermentations are typically more dilute than high starch grain-based fermentations, and the ethanol concentration is therefore significantly lower [5–7]. Dilution is a problem when distillation is used as the alcohol recovery method, since distillation energy use (and cost) rises exponentially as distillation feed concentration drops to the range expected for lignocellulosic feedstocks [7–9].

Solvent extraction is an alternative to distillation for recovering ethanol from aqueous solutions such as fermentation broths. Solvent extraction has been the subject of much research interest, in part because it has the potential to be less energy intensive than distillation. The primary energy saving stems from the reduced quantity of water that is vaporized compared to distillation. For solvent extraction vaporization occurs in the solvent regeneration step where the ethanol and water that partitioned into the solvent phase are removed. However, to compete commercially with distillation, extraction processes require better performing solvents.

There are various ways to operate a fermentation and extraction system, and the method chosen will determine the criteria for solvent selection. When the end product of the fermentation is inhibiting (as is the case for ethanol or butanol production), fermentor productivity can be significantly increased by continuous removal of the product by extraction [10–12]. In this process, the solvent contacts the fermentation broth or a cell-free portion of the broth, and after disengagement from the solvent, the aqueous phase is returned to the fermentor. Some important criteria for solvent selection are [13]: (1) good extraction performance (i.e., partitioning of the product between the solvent and aqueous phases), (2) low solvent solubility in the aqueous phase, (3) low solvent toxicity (to workers, to the environment, to fermentation microorganisms), (4) effective product recovery from the solvent and its regeneration, (5) rapid phase separation, (6) chemical stability, (7) acceptable solvent handling properties (low melting point, compatible with preferred materials of construction), and (8) a low level of stable emulsion or foam formation. Also, the solvent should not support growth of contaminant or ethanologenic organisms in the fermentation system, as this will contribute to solvent loss.

An alternative is a batch fermentation where the raffinate is not directly returned to the fermentor. In this case the requirement

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that the solvent be non-toxic to the fermenting microorganism is reduced or eliminated, depending on in-plant water reuse and treatment.

It is common for ethanol plants using grain feedstocks to produce a high-protein animal feed as a co-product. For this application, any residual solvent in this co-product must be safe for the animals to which it is fed, and not diminish the value of products derived from those animals.

A membrane contactor provides an alternative to direct mixing of the aqueous and solvent phases, which has the advantages of eliminating the need for disengagement of the solvent and aqueous phases, and the need to balance the flows of the two phases to avoid flooding conditions in the extractor. This removes the need for the criteria of rapid phase separation and minimization of stable emulsions or foams.

The functional groups contained in the solvents are a primary determinant of extraction performance, with ethanol capacity generally following the experimentally-determined order carboxylic acids > alcohols > esters > amines > ketones > ethers > hydrocarbons [14–16]. In previous papers, we have studied alcohols, esters, and vegetable oils to identify important structural parameters within a class [17,18]. For the alcohols, it has been shown that the ethanol capacity of the alcohol decreases as molecular weight increases. Structural differences such as branch position and size have an effect [14,15]. In addition, we have shown that position of the hydroxyl group [17,19] has a significant effect on selectivity due to the extended hydrogen-bond structure of the solvent molecules. For alcohol isomers of the same molecular weight, separation factor improves when the hydroxyl group is located closer to the middle of the molecule, and when the primary and secondary chains are branched [20].

Several authors [21–23] have developed computer-aided approaches to solvent selection. Estimation of liquid–liquid equilibria (LLE) most commonly uses the UNIFAC group contribution method. This method is useful for qualitative rankings of performance within solvent classes [24]. However, as Pretel et al. [25] point out, the method does not take into account the positioning of the groups within the molecule. Hence, all isomers of a compound are predicted to have the same LLE behavior, which is not the case. Meniai et al. [26] address this problem by calculating interaction parameters between two whole molecules. Biocompatibility of solvents with three ethanologenic microorganisms was correlated by Bruce and Daugulis [24] with log *P*, the octanol/water partition coefficient of the solvent. They found that a solvent would be toxic if its log *P* were above a certain value, which differed for each microorganism.

Munson [27] shows data comparing the extraction performance of 1-hexanol, 1-octanol and 2-ethyl-1-hexanol with the corresponding acids, and notes an increase in separation factor for all three acids, with a reduced capacity for the two C8 examples. The higher selectivity of the acids vs. the alcohols is attributed to the expectation that stronger Lewis acids will be more selective for ethanol since ethanol has a slightly larger donor number and lower acceptor number than water.

Boudreau and Hill [28] studied valeric, hexanoic, octanoic, nonanoic and oleic acids in partitioning at 25 °C from ethanol/water solutions in the range of 0.01–0.08 g/mL ethanol. They found that the ethanol distribution coefficient decreased as the molecular weight of the solvent increased, as did the water distribution coefficient. Their preferred solvent was nonanoic acid, which had an acceptable balance of ethanol capacity, low water solubility, and low volatility for good recovery of ethanol from the solvent in a flash process. Simulations of a flash separation step recovering 90% of the ethanol in a 10 g/dL feed to achieve a 69.5 wt% ethanol product used only 62% of the energy required by distillation to reach the same purity.

Jassal et al. [29] carried out flash studies to simulate recovery of ethanol from oleic acid that had been equilibrated with ethanol/water solutions. They report that the steam requirement to produce 0.851 mole fraction ethanol (93.6 wt%) from 8 wt% feed via oleic acid extraction and flash recovery is 34% of the steam required for distillation to the same purity.

Barros et al. [30] studied valeric, hexanoic, octanoic and oleic acids as solvents in an extractive fermentation process producing ethanol using free and gel-entrapped yeast cells. They found that valeric, hexanoic and octanoic acids totally inhibited cell growth, while oleic acid was not inhibitory to immobilized cells, but had some inhibition in the free suspended cell system at high solvent/medium ratios.

In the present work, we investigate carboxylic acids that are analogs of the high-performing β-branched alcohols (Guerbet alcohols) studied previously [20]. Like the analogous alcohols, these acids are commercially available, and in fact are made by oxidation of the corresponding alcohols [31]. They have several desirable characteristics, such as low melting points equal to linear acids that are half their carbon chain length, high boiling points, and very low solubilities in water. They are used in cosmetics, pharmaceuticals, personal care, and metalworking, and as chemical intermediates for esterification, alkoxylation, conversion to betaines, and amidation reactions. In this work, we had particular concerns that pH could affect partitioning results, solubility of the acids in the aqueous phase, and disengagement of the aqueous and organic phases due to the surfactant-like properties of the higher carboxylic acids.

2. Experimental

2.1. Measurement of ethanol and water partitioning

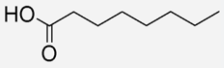
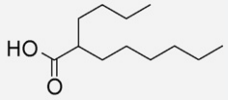
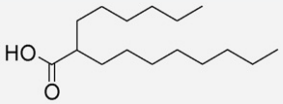
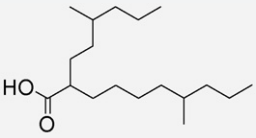
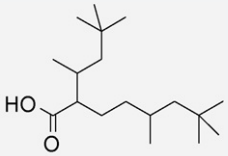
The solvent screening technique developed previously [32] was employed to measure the partition of ethanol and water between an aqueous phase, initially 5 wt% ethanol, and the solvent phase. Multiple extractions were carried out for each compound, and the results averaged. Extractions were at 33 °C with an aqueous-to-organic phase volume ratio of 2:1 and a total liquid volume of 7.5 mL. The mixtures were emulsified multiple times to ensure equilibration, then phase-separated by centrifugation at the extraction temperature. Gas chromatography using a thermal conductivity detector and an internal standard method was employed to determine the equilibrium ethanol and water concentrations in the organic phase, and the ethanol concentration in the aqueous phase. The water concentration in the aqueous phase, $[H_2O]_{aq}$, was taken to be $1 - [EtOH]_{aq}$. This assumption is valid because the tested solvents have a low solubility in the aqueous phase. A difference between the method used here and that presented previously is the use of anhydrous benzyl alcohol rather than 1-butanol as the organic-phase diluent.

For each acid solvent, partitioning data was taken with the initial 5 wt% ethanol aqueous phase at its unadjusted pH of 5.9. For all but iso-stearic acid, a second set of extractions were done with the initial aqueous phase adjusted to pH 3.4 with 1N HCl. For iso-stearic acid, a second set of extractions were done with the initial aqueous phase adjusted to pH 9.9 with 50% NaOH.

2.2. Solvents and materials

The extraction solvents and their sources are shown in Table 1. These materials were used as received. Two unbranched acids, 1-decanoic and 1-dodecanoic, are obvious choices for inclusion, but as they are solids at the extraction temperature, they were not included. Ethanol used in the extractions was from Aaper Alcohol and Chemical Co., >99.5%, undenatured (labeled 200 proof,

Table 1
Solvents investigated.

Common name	Purity	Source	Chemical name	CAS	Structure
Caprylic acid	99.7%	Aldrich	Octanoic acid	124-07-2	
Iso-lauric acid	99.7%	Aldrich	2-Butyloctanoic acid	27610-92-0	
Iso-palmitic acid	219 mg KOH/g[a] (100% of theoretical)	Nissan Chemical	2-Hexyldecanoic acid	25354-97-6	
Oleic acid	99%	Aldrich	*cis*-9-Octadecenoic acid	112-80-1	
Iso-stearic acid N	195 mg KOH/g[a] (98.9% of theoretical)	Nissan Chemical	2-(3-Methyl hexyl)-7-methyl decanoic acid	30399-84-9	
Iso-stearic acid	196.2 mg KOH/g[a] (99.5% of theoretical)	Nissan Chemical	2-(1,3,3-Trimethyl butyl)-5,7,7-trimethyl octanoic acid	54680-48-7	

[a] Acid value: mg KOH required to neutralize the free fatty acids in 1 g of sample.

absolute, anhydrous, ACS/USP grade). For the analysis, the organic-phase diluent was anhydrous benzyl alcohol (Aldrich, 99.99%) that was stored over 3 A molecular sieves to maintain dryness. The aqueous phase internal standard was 1-butanol (Aldrich, 99.95%), and the organic-phase internal standard was anhydrous 1-hexanol (Aldrich, 99.49%). Water deionized by reverse osmosis was used in all solutions.

2.3. Yeast toxicity evaluation

The evaluation of the solvent toxicity or inhibition to yeast follows that of the biocompatibility tests described by Kollerup and Daugulis [22]. Briefly, flasks containing a sterilized glucose-based growth medium were inoculated with fermentation broth from a 24-h-old yeast culture and incubated at 30 °C in a rotary shaker bath for 8 h. At this point the cells were vigorously growing and 10 mL of solvent was added to the 55 mL culture in each flask. After a further 24 h, the flasks were sampled and analyzed for ethanol, residual glucose, dry cell weight, and cell viability. Results were compared to those of a solvent-free control culture. The yeast was Red Star® Ethanol Red™, a strain of *Saccharomyces cerevisiae* that has been developed for the fuel alcohol industry, supplied by Fermentis, a division of S. I. Lesaffre Yeast Corp. It is described as a fast-acting, temperature tolerant dry yeast that displays higher alcohol yields and maintains higher cell viability during fermentation as compared with standard distiller's yeast.

3. Results and discussion

3.1. Ethanol and water partitioning performance

Ethanol extraction performance comparisons of solvents at fixed operating conditions can be conveniently represented by two parameters: ethanol distribution coefficient K_{DE} and separation factor α. The ethanol distribution coefficient indexes the solvent's capacity for ethanol, while the separation factor is the solvent's selectivity for ethanol over water. The equilibrium distribution coefficient for ethanol is defined as the ratio of the weight percent of ethanol in the organic phase to the weight percent of ethanol in the aqueous phase:

$$K_{DE} = \frac{[EtOH]_{org}}{[EtOH]_{aq}} \quad (1)$$

The equilibrium distribution coefficient for water is defined similarly:

$$K_{DW} = \frac{[H_2O]_{org}}{[H_2O]_{aq}} \quad (2)$$

The separation factor is the ratio of ethanol to water in the organic phase divided by the ratio in the aqueous phase, or:

$$\alpha = \frac{K_{DE}}{K_{DW}} \quad (3)$$

Table 2
Measured ethanol partition coefficients and separation factors.

Solvent	pH, initial	pH, final	Runs	K_{DE} (S.D.)	α (S.D.)
Octanoic acid	5.9	3.5	2	0.649 (0.0049)	13.5 (0.19)
	3.4	2.5	2	0.655 (0.0014)	14.0 (0.04)
	Combined		4	0.652 (0.0048)	13.8 (0.28)
2-Butyloctanoic acid	5.9	4.5	5	0.267 (0.0074)	31.8 (1.31)
	3.4	3.0	2	0.262 (0.0042)	32.5 (0.071)
	Combined		7	0.265 (0.0066)	32.0 (1.14)
Iso-palmitic acid	5.9	4.5	4	0.170 (0.0037)	37.5 (2.29)
	3.4	2.5	1	0.169	38.6
	Combined		5	0.169 (0.0032)	37.7 (2.04)
Oleic acid	5.9	4.5	4	0.191 (0.019)	26.8 (2.49)
	3.4	2.8	2	0.160 (0.0035)	26.4 (0.035)
	Combined		6	0.180 (0.022)	26.7 (1.95)
Iso-stearic acid N	5.9	4.8	3	0.151 (0.0025)	43.0 (1.53)
	3.4	2.5	2	0.151 (0.0021)	41.6 (0.28)
	Combined		5	0.151 (0.0021)	42.4 (1.33)
Iso-stearic acid	5.9	5.0	4	0.136 (0.011)	40.2 (1.19)
	9.9	5.0	2	0.142 (0.0028)	41.9 (1.18)
	Combined			0.138 (0.0091)	40.7 (1.38)

Table 2 displays the partitioning results at each of the two starting pH values, the final pHs, the number of extraction runs, and the standard deviations of the results. In comparing partitioning results with the initial 5 wt% ethanol aqueous phase at its unadjusted pH of 5.9 to those with the initial phase adjusted with 1N HCl to pH 3.4, or for iso-stearic acid to 9.9 with NaOH, we did not see a significant difference in behavior due to pH. Therefore, combined results for each of the solvents is also shown in the table.

3.2. Solvent toxicity to yeast

The results from the shaker flask experiments to determine each solvent's toxicity or its inhibitory effects on yeast cell growth and ethanol production, are shown in Table 3. There is a very clear difference between the results for the C8 and C12 acids and the C16–C18 acids. Yeast contacted with the lower molecular weight acids resulted in greatly reduced ethanol production and glucose consumption, cell weight, and cell viability by both staining and by plate count compared to the solvent-free control flasks. For the higher molecular weight acids, ethanol production, glucose consumption, cell growth, and cell viability were essentially equivalent to the solvent-free controls.

The data for ethanol production, glucose consumption, and cell viability by the staining technique show low % errors of <10% among nine solvent-free controls and for duplicated tests with solvents above C12. Cell dry weight and cell viability by plate count show much higher % errors in all cases and are less trustworthy.

3.3. Comparison of acids to alcohols

Fig. 1 displays α and K_{DE} experimental data for the acids and previously reported analogous alcohol data [20]. In all cases, the acids show a lower ethanol distribution coefficient K_{DE}, and a larger separation factor α, relative to the corresponding alcohol. The acids seem to follow the general isomeric behavior of the alcohols with larger separation factor when the acid group is located near the middle of the molecule and by branching of the alkyl chains. Oleic acid, a C18 primary alcohol, has a separation factor of 26.7; the two branched C18 acids with the carboxylic acid group near the middle of the molecule have separation factors of 40.7–42.4, or about 50% higher than that of oleic acid.

In Table 4, reported properties and experimental performance of the acids are compared to those of alcohols of similar structure. In general, melting point, boiling point, and specific gravity values are higher for the acids than the corresponding alcohols, reflecting the stronger molecular association of the acids in the bulk solvent. Barton [33] reports solubilities of the alcohols and Eggenberger et al. [34] report solubilities of the fatty acids. The acids of lower molecular weight have a higher solubility in water than the corresponding alcohols. Above C12, solubilities are too low for both classes of solvents for conventional analysis.

The toxicity to yeast of the acids follows the trend seen for the corresponding alcohols [20], with C16 and higher acids being non-toxic, and C12 and lower acids being toxic to the yeast.

3.4. Solvent losses to the raffinate

In a typical solvent extraction process the phases are separated after the last extraction stage and the solvent phase is processed to recover the product and regenerate the solvent for reuse. The solvent level in the raffinate is an important consideration, and needs to be low, as it can represent a potential loss of solvent from the

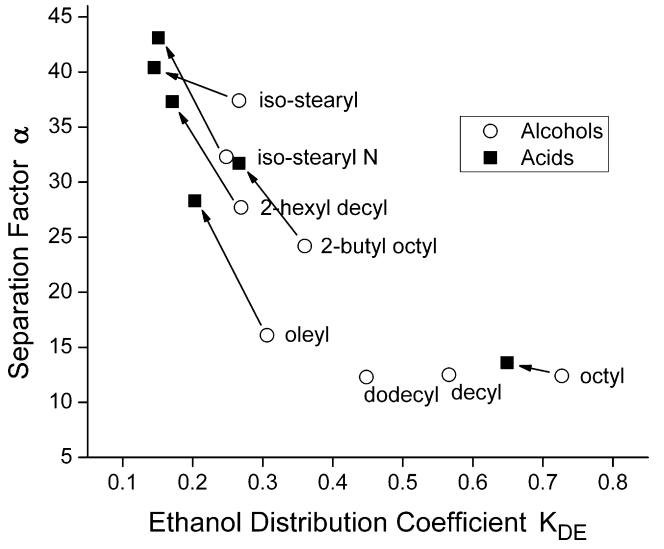


Fig. 1. Ethanol extractive performance of aliphatic acid and alcohol solvents at 33 °C and 5 wt% initial ethanol concentration. Open circles are alcohols, filled squares are the corresponding acids.

Table 3
Solvent toxicity to yeast.

Solvent		Ratios to controls				
Name	No. of carbons	Ethanol produced	Glucose consumed	Cell dry weight	Cell viability, staining	Cell viability, plate count
1-Octanoic acid	8	0.06	0.00	0.62	0.00	0.00
2-Butyl-1-octanoic acid	12	0.13	0.26	0.52	0.00	0.00
Iso-palmitic acid	16	0.97	1.00	1.16	0.91	1.67
Oleic acid	18	0.95	1.00	1.94	0.75	1.10
Iso-stearic acid N	18	0.97	1.00	1.49	0.97	0.78
Iso-stearic acid	18	0.98	1.00	1.50	0.89	1.67

process. Make-up solvent must be purchased, and the lost solvent must be taken into account in the downstream processes, including waste treatment. Solvent losses can be due to several factors, such as solvent solubility in the raffinate, incomplete phase separation due to formation of emulsions, and entrainment of small droplets or micellar structures.

The solubility of the acids drops markedly as molecular weight increases (see Table 4), reaching ppm levels for the higher acids. However, data for the oleic acid–ethanol–water system reported by Zhang and Hill [35] indicated acid present in the aqueous phase at roughly 200 ppm. It should be noted that the oleic acid used by Zhang was a commercial grade, with about 25% being a mixture of other acids of mostly lower molecular weight. The titration method for determining acid content in the aqueous phase reported the sum of all acids present in the aqueous phase as oleic, thereby overestimating the concentration of oleic acid present.

Analysis of acid dissociation behavior can provide insight to solubility and entrainment issues in these systems. Fatty acid salts are well-known surfactants and their use as soaps dates back over 4000 years to ancient Babylon and Egypt. The dissociated acid molecules are more soluble in water, plus they have a stronger tendency to form micelles and emulsions than the undissociated acid. For the situation of fuel ethanol production, the pH of the fermentation broth will be 4–5 due to saturation with carbon dioxide produced in the fermentation. The pK_a of the lower carboxylic acids is around 4.8 [36], hence at a pH of 4.8 the lower acids would be 50% dissociated. However, alkyl chain length is an important factor in affecting the apparent pK_a of the higher carboxylic acids. Kanicky and Shah [36] show that the apparent pK_a is constant for C2–C6 fatty acids, but rises with chain length for fatty acids above C6: a C14 fatty acid has an apparent pK_a of about 8, C16 of about 9, and C18 of 9.5–10. The reason they propose for this behavior for the longer chains is that molecular packing between the carboxylic acid molecules at the interface is tighter due to van der Waals interactions between the chains and consequently the surface concentration increases and the distance between molecules decreases. The proximity of other charged groups to any given carboxyl group stabilizes the acid proton, hence the measured pK_a increases. This argument also applies to micellar or pre-micellar aggregates that may be present in the aqueous phase. If this argument also holds for the branched-chain C16 and C18 carboxylic acids studied here, the ratio of dissociated (higher solubility)-to-undissociated species would be expected to be very low at pH 4–5, and losses due to solubility to the aqueous phase would be negligible. In our extraction studies, the carboxylic acid solvents were below the detection limit of 100 ppm by GC of the aqueous phase (typically containing ~4.5 wt% residual ethanol) after emulsification and phase separation. No solubility data for the solvents in fermentation broth was obtained.

Stable associations (clusters) of solvent molecules may be present in the aqueous phase (i.e., micelles or pre-micellar associations). Solvent losses due to this effect are likely to be larger than from simple solubility of the acid in water, but depend on (1) generation of solvent clusters due to hydrodynamic forces at the solvent/aqueous phase interface that entrain solvent molecules or clusters into the aqueous phase, and (2) removal of solvent clusters via coalescence and density difference. Both depend on the equipment and residence times used for the extraction and subsequent phase separation.

3.5. Estimated effect of entrainment of aqueous phase in the organic phase

Entrainment of aqueous phase in the organic phase can seriously degrade overall performance in an industrial application. We have estimated how the separation factor can be changed by aqueous phase entrainment in the organic phase, as shown in Fig. 2. The basis is $\alpha = 50$, $K_{DE} = 0.16$, and $[EtOH]_{aq} = 5$ wt%. For instance, 0.5 wt% aqueous phase entrained in the organic phase reduces the separation factor from 50 to 20.1. The concentration of the solvent-free extract is 72.5 wt% ethanol with no entrainment,

Table 4
Comparison of properties and extraction performance of selected carboxylic acids and alcohols.

Name	No. of Cs	MP, °C	BP, °C	S.G., 20/20 °C	Solubility in water, mg/L$^{T,°C}$	Ethanol produced[a]	α	K_{DE}
1-Octanol	8	−15	196	0.83	540^{25}	0.17	12.4	0.727
Octanoic acid	8	15–17	237	0.91	789^{30}	0.06	13.8	0.652
1-Decanol	10	5–7	231	0.83	37^{25}	0.13	12.5	0.566
Decanoic acid	10	27–32	268–270	0.90	64^{30}	Solid at extraction temperature		
1-Dodecanol	12	22–26	260–262	0.84	4^{25}	0.17	12.3	0.448
Dodecanoic acid	12	44–46	299	0.89	$<8^{30}$	Solid at extraction temperature		
2-Butyl-1-octanol	12	<−30	145–149	0.84		0.53	24.2	0.360
2-Butyloctanoic acid	12		230	0.89		0.13	32.0	0.265
2-Hexyl-1-decanol	16	−21 to −15	193–197	0.84		1.00	27.7	0.269
Iso-palmitic acid	16	−3	268	0.88		0.97	37.7	0.169
Oleyl alcohol	18	0–5	207	0.85		1.02	16.1	0.306
Oleic acid	18	13–14	194–195	0.89		0.95	26.7	0.180
Iso-stearyl alcohol (FO-180 N)	18	<−30	306	0.85		0.99	32.3	0.248
Iso-stearic acid N	18	−30	320	0.88		0.97	42.4	0.151
Iso-stearyl alcohol (FO-180)	18	<−30	295	0.84		1.01	37.4	0.266
Iso-stearic acid	18	−20	311	0.88		0.98	40.7	0.138

[a] Ratio of ethanol produced by yeast in contact with solvent to solvent-free control.

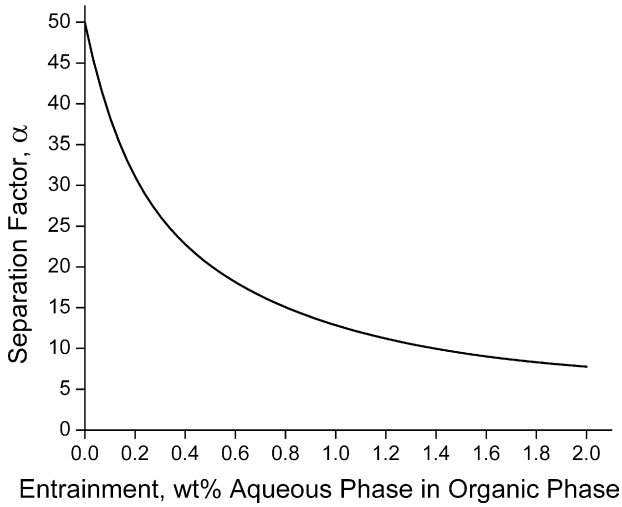


Fig. 2. Theoretical effect of aqueous phase entrainment on separation factor for a solvent with partitioning performance of $\alpha = 50$, $K_{DE} = 0.16$, $[EtOH]_{aq} = 5$ wt%.

but with 0.5 wt% entrainment, this reduces to 51.4 wt% ethanol. High molecular weight carboxylic acids as used here may stabilize aqueous phase microdroplets in the organic phase. As a general cautionary note to researchers acquiring partitioning data, a clear organic phase is not a guarantee of complete disengagement of the phases–microdroplets below 10 nM in diameter will not be visible as a hazy or cloudy mixture. In an industrial process, the use of membrane contactors would be expected to reduce or eliminate this effect.

4. Conclusions

The C12–C18 β-branched carboxylic acids have low K_{DE} values, but a large range of α values that reflect the influence of hydroxyl position and branching, similar in behavior to alcohols of similar structure. The pH of the aqueous phase did not appear to have a significant effect on partitioning performance. Although it would be very desirable to be able to use lower molecular weight carboxylic acid solvents that have high K_{DE} values, higher solubility in the raffinate and toxicity to fermenting yeast exposed to the solvents would preclude their use in extractive fermentations. On the other hand, the C16–C18 carboxylic acid solvents have reduced solubilities in the raffinate compared to the smaller carboxylic acids and are non-toxic and non-inhibitory to the Ethanol Red™ yeast strain often used for fuel ethanol production. Compared to alcohols of similar structure, the acids have lower values for K_{DE}, but higher values of the separation factor α. Yeast toxicity results for the acids follow a similar pattern to that of the analogous alcohols.

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